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SIMULATION OF MICROSTRUCTURE EVOLUTION DURING HOT WORKING[1]

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Abstract
Finite element method is already large used in the simulation of thermo mechanical processes in industrial scale. However, further progress is needed regarding to the microstructure optimization of components produced by metal forming processes such as hot forging or rolling. This paper aims to present mathematic models to predict microstructure evolution during hot working, showing an application of mathematical models coupled to thermo mechanical processes simulation software.
Key words: Recrystallization; Hot forging; Microstructure evolution.

SIMULAÇÃO DE EVOLUÇÃO MICROESTRUTURAL DURANTE O TRABALHO A QUENTE

Resumo
O método dos elementos finitos já é largamente utilizado na simulação de processos termomecânicos em escala industrial. No entanto, maiores progressos são necessários em relação à otimização da microestrutura de componentes produzidos por processos de conformação mecânica como o forjamento ou laminação a quente. Este artigo aborda modelos matemáticos para previsão de microestrutura durante o trabalho a quente, apresentando uma aplicação do acoplamento de modelos em um *software* de simulação numérica para processos termomecânicos que emprega o método de elementos finitos.
Palavras-chave: Recristalização; Forjamento a quente; Evolução microestrutural.

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1 INTRODUCTION

Softwares based on Finite Element Method (FEM) focused on metal forming processes can provide technical results such as final geometry, temperature and equivalent strain distribution, stress distributions, load needed to forming process, etc. However, for information related to the microstructural evolution during hot work it is necessary to incorporate into FEM software mathematical models describing the kinetics of recrystallization along the process taking in consideration grain size refinement and grow. By the incorporation of such mathematical models it is possible to predict the forming process as a whole, including the final microstructure obtained for the forged part, allowing process optimization focusing a higher quality final product. This paper aims to review static and dynamic phenomena during hot working and the coupling of mathematical models for the microstructure evolution kinetics to Finite Element Method software.

1.1 Microstructure Evolution During Hot Working

At low temperatures, work hardening mechanisms such as increasing dislocation density lead to an increase in stress necessary to further deformation. However, in processes carried out at high temperatures, such as forging and rolling, diffusion processes become important and microstructural phenomena such as recrystallization and recovery can occur, modifying the material flow behavior during the process. These phenomena which occur during deformation are known as dynamic recovery and dynamic recrystallization.[1,2]
For metals, especially those with high stacking fault energy, above 0,1 J/m^2, work hardening is limited by dynamic recovery.

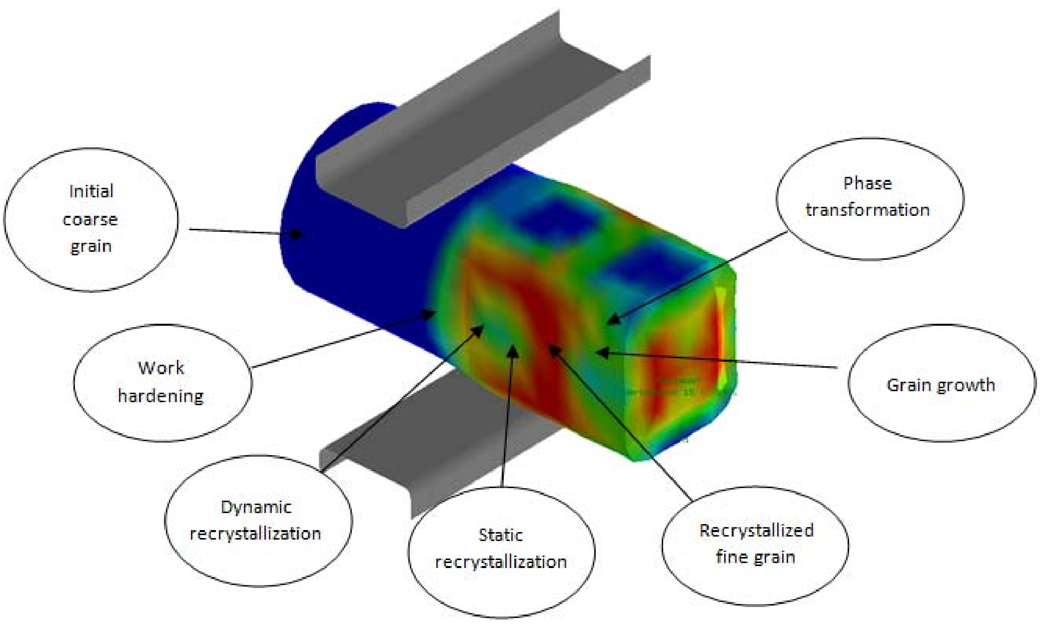

Figure 1. Microstructural changes during hot working.

Dynamic recovery can be conceptualized as a dynamic equilibrium between the rates of generation and annihilation of dislocations during deformation, resulting in a continuous rearrangement of these dislocations, which leads to a softening on the material, limiting the effect of work hardening.[3]

For materials that exhibit low stacking fault energy, as is the case of steel in the austenitic phase, dynamic recovery is less effective. In these materials the softening governing mechanism is dynamic recrystallization, determining the stress-strain curve of the material and, hence, its flow behavior.
As the material is deformed, a large number of defects are generated. These defects, which are not completely eliminated by dynamic recovery, increase thermodynamic potential for the onset of recrystallization. As soon as a critical deformation is reached (ε_c) the nucleation of new grains free of deformation starts along preferential sites such as grain boundaries.(2) This phenomenon generates a strong softening on flow curve at the same time that provides a strong grain size refinement. Besides the chemical composition and initial microstructure, dynamic recrystallization is strongly dependent on the temperature, strain and strain rate applied to the material.(3-5)

1.2 Recrystallization Kinetics

For metal forming processes such as hot forging and rolling, control of recrystallization and related conditions can provide a higher quality product. Through mathematical models it is possible to predict the material microstructure evolution during the forming process, describing the kinetics of dynamic recrystallization, static and changes in grain size.
The combination of temperature, strain rate and activation energy can be described by introducing the Zener-Hollomon parameter (Equation 1).(5,6)

$$Z = \dot{\varepsilon} \, . \, exp\left(\frac{Q_{DRX}}{R.T}\right) \qquad (1)$$

Where: $\dot{\varepsilon}$ = strain rate (s^{-1}); T = forming temperature (K); Q = activation energy (J/mol); R = universal gas constant (8,314 $J.mol^{-1}.K^{-1}$).
Dynamically recrystallized grain size is directly dependent on the parameter Z and can be calculated by Equation 2.(7)

$$d_{DRX} = b \, . \, Z^{b_1} \qquad (2)$$

The dynamic recrystallization (DRX) kinetics follows a modified Avrami-type equation and can be calculated by Equation 3.(6,7)

$$X_{DRX} = 1 - exp\left(d_1 \, . \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_{ss} - \varepsilon_c}\right)^{d_2}\right) \qquad (3)$$

Where: ε_c= critical strain to onset of dynamic recrystallization; ε_{ss} strain to onset of steady-state; d_o= initial austenitic grain size; d_1 e d_2 = material-dependent parameters.
The critical strain ε_c corresponds to a critical dislocation density required to initiate dynamic recrystallization shown by Equation 4.

$$\varepsilon_c = 5{,}6.10^{-4}.d_0^{0{,}3}.Z^{0{,}17} \qquad (4)$$

Not all of work hardening can be eliminated during hot working. After forming, or between different stages during the process, microstructural phenomena continue occurring to eliminate the work hardening until reaching the steady state of microstructural organization. These phenomena are the static recovery and static recrystallization.(7,8) The static recrystallization (SRX) kinetics (Equation 5), also follows a modified Avrami-type equation and can be calculated by Equation 5.(8,9)

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$$X_{SRX} = 1 - exp\left(-0{,}693\,.\left(\frac{t}{t_{0,5}}\right)^{k}\right) \qquad (5)$$

Where $t_{0,5}$ is the time needed for 50% static recrystallization and can be obtained by Equation 6.

$$t_{0,5} = f_1\,.\,d_0^{f_2}.\,\varepsilon^{f_3}.\,exp\left(\frac{Q_{SRX}}{R.T}\right) \qquad (6)$$

Static recrystallized grain size can be calculated by Equation 7.

$$d_{SRX} = c_1.\,d_0^{c_2}.\,\varepsilon^{c_3}.\,Z_m^{c_4} \qquad (7)$$

Where: d_0= initial austenitic grain size; t = time interval between stages; k,c_i, f_i = material-dependent parameters.
When recrystallization is over, following grain growth (Equation 8), occurs if the material is still exposed to high temperatures. According to Sellars, grain growth can be calculated by Equation 8.[9,10]

$$d_{gg} = d_0^{hd_2} + h.\,d_3.\,t.\,\exp\left(\frac{-Q_{gg}}{R.T}\right) \qquad (8)$$

All material dependent parameters present in equations above {a_i, b_i, c_i, d_i, e_i, f_i, g_i} should be experimentally determined using regression analysis and metallographic techniques. Methods of how to obtain these parameters are described in the literature.[9-12]
By the incorporation of mathematical models presented above in different plastomechanical numerical simulation software is possible to obtain microstructural prediction during hot working.

2 MATERIALS AND METHODS

2.1 Simulation of an Upsetting Test with Microstructure Evolution

To demonstrate the simulation of a plastomechanical process with microstructural evolution, a numerical simulation software was used and the flow curves and microstructural parameters of DIN 42CrMo4 steel were collected and inserted into the software. The software used was PEP/Larstran, which is an open source academic software developed by the Institute of Metal Forming (IBF) at the Technical University of Aachen (RWTH), Germany. PEP/Larstran works coupled with the microstructure module called Strucsim. For each increment of the forming process simulation iterations between the plastomechanical and microstructure modules are executed. The plastomechanical module feeds the microstructure module with the instantaneous values of equivalent strain, strain rate and temperature. The microstructure module then calculates the microstructural evolution depending on the values fed and taking into account the previous microstructural state. For each new microstructure condition the flow curve of the material is recalculated according to the Equation 9.[7]

$$\sigma = \sigma_m\,.\left(\frac{\varepsilon}{\varepsilon_m}.\,\exp\left(1-\frac{\varepsilon}{\varepsilon_m}\right)\right)^{c_2\left(1-\exp\left(c_3(\ln Z)^{c_5}\right)\right)+c_4} \qquad (9)$$

Where: $\varepsilon_m = a_1.\,D_0^{a_2}.Z^{a_3}$ and $senh(a_3.\sigma_m) = a_1.Z^{a_2}$.

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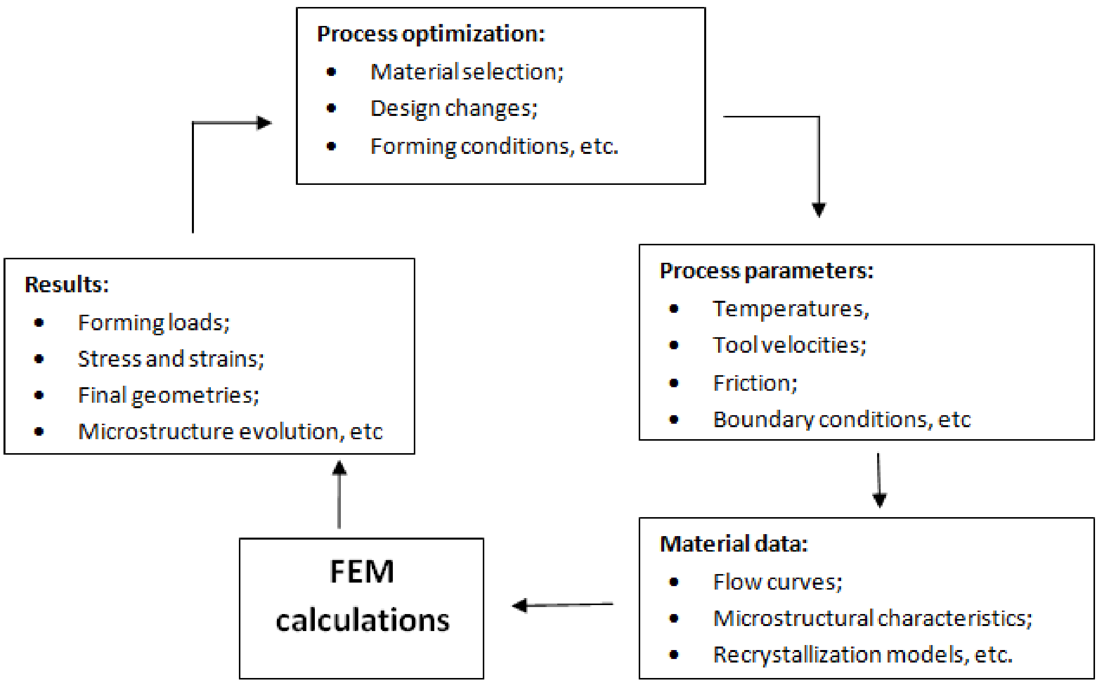

Figure 2. Flow chart for steps in an integrated plastomechanical and microstructure simulation.

The study carried out was the simulation of a hot upsetting test of a cylindrical workpiece (Figure 3). The numerical model reproduces usual test conditions, using the parameters shown in Table 1.

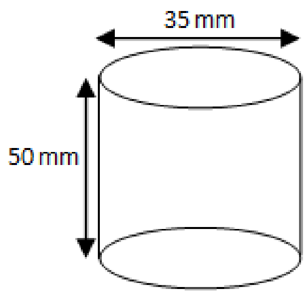

Figure 3. Dimensions of workpiece used for the simulations.

Table 1. Parameters used for the simulation

Parameter	Value
Material	DIN 42CrMo4
Fricton coefficient	0,3
Reduction in height	25 mm
Workpiece temperature	900°C
Tool speed	3,7 mm/s
Mesh	Hexaedric 8 nodes
Number of elements	2280

To better visualize the results, a longitudinal cutting is made on cylinder deformed, and the results evaluated were: effective strain, strain rate, dynamically recrystallization (DRX) and dynamically recrystallized grain size.

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3 RESULTS AND DISCUSSION

Figures 4, 5, 6 and 7 illustrate the results obtained by the simulation. The first observation is the expected barrel effect of the cylinder due to frictional forces between the cylinder and tools. Figures 4a, 5a, 6a and 7a illustrate the distributions of effective strain, strain rate, DRX and dynamically recrystallized grain size, respectively, along the longitudinal cutting while Figures 4b, 5b, 6b and 7b illustrate the change in effective strain, strain rate, DRX and dynamically recrystallized grain size along the centerline of the workpiece. From Figure 4a is possible to observe that deformation is higher in the center of workpiece, probably due to the frictional forces existing between workpiece and tool surfaces, restricting material flow along this region.

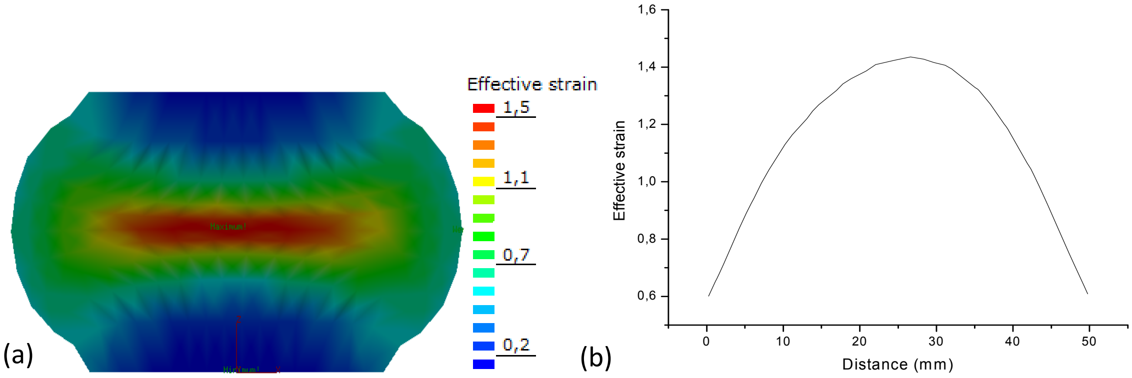

Figure 4. (a) Longitudinal cutting illustrating effective strain distribution; and (b) change in effective strain along the centerline of the workpiece.

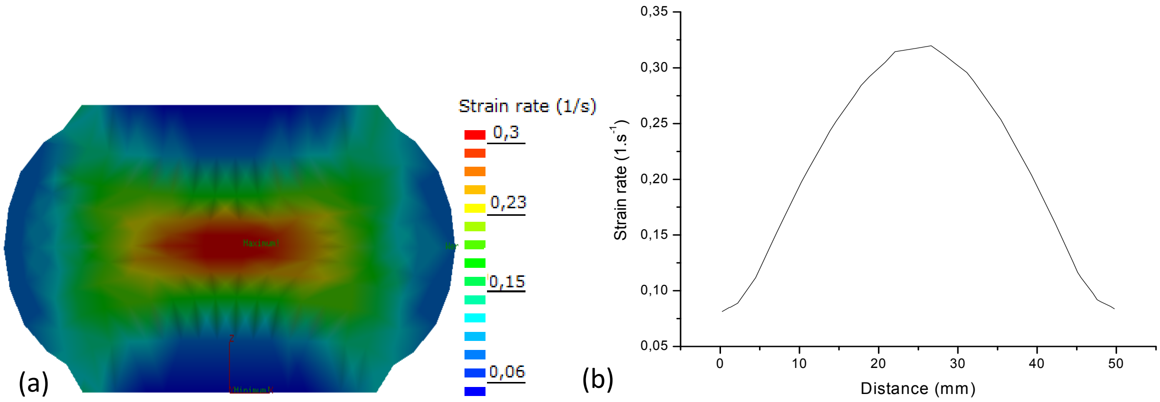

Figure 5. (a) Longitudinal cutting illustrating strain rate distribution; and (b) change in strain rate along the centerline of the workpiece.

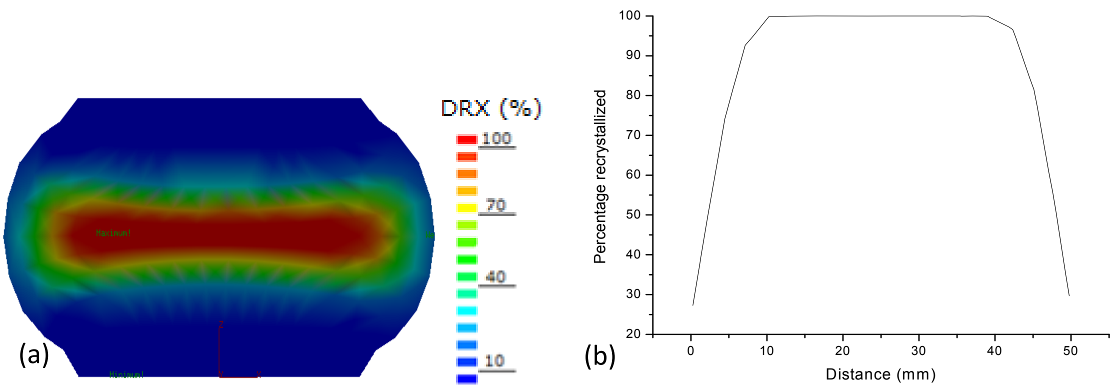

Figure 6. (a) Longitudinal cutting illustrating percentage DRX; and (b) change in percentage DRX along the centerline of the workpiece.

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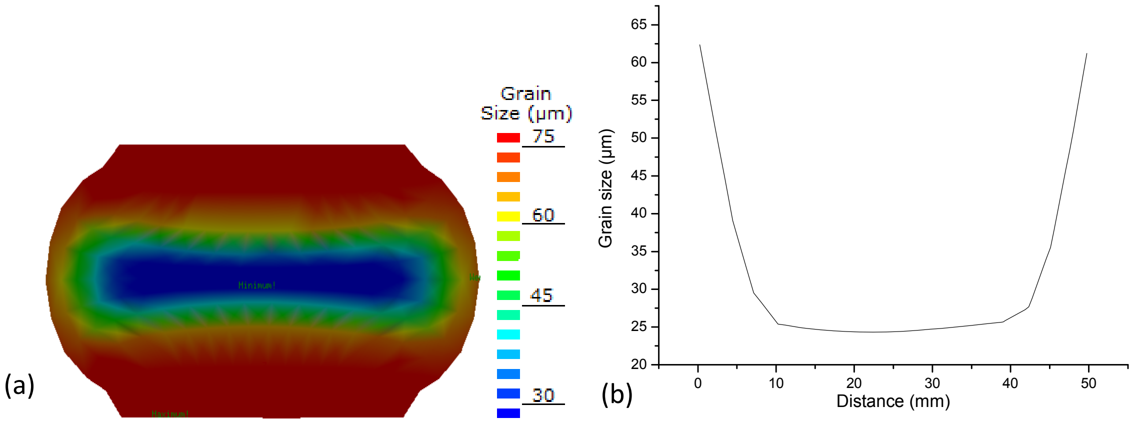

Figure 7. (a) Longitudinal cutting illustrating recrystallized grain size; and (b) change in recrystallized grain size along the centerline of the workpiece.

Figure 5a illustrates the distribution of strain rate along the workpiece. Strain rate can be calculated by: $\dot{\varepsilon} = \frac{v}{h}$. (10)
Where v = upper tool speed ($mm.s^{-1}$); and h = height (mm).
Solving Equation 10 for the central region of the workpiece, it is obtained:

$$\dot{\varepsilon} = \frac{3{,}7}{12{,}5} = 0{,}296\ s^{-1}$$

This value will in accordance to the average strain rate in the central region obtained by simulation (Figures 5a and 5b). As the effective strain and strain rate are greater in the central region, it is expected that DRX will be greater which can be seen from Figure 6. Figure 6a shows that recrystallization occurs most severely in the central region, providing a strong grain size refinement, starting from an average grain size of 75 μm along the regions near surface to about 30 μm in the central region (Figures 7a and 7b).
According to FEM results is clear that recrystallized fraction increases with increasing strain, after reaching the critical strain to onset of dynamic recrystallization. Strain depends, among other factors, tool geometries, friction conditions and strain rate. Therefore, it is possible through FEM to have a control of these factors and the process in general, as a prediction in terms of process values such as forming loads and temperature gain/loss as microstructure evolution, eliminating costly steps of tooling, prototypes and metallographic procedures that would be required without the FEM coupled with microstructure evolution.
However, further improvements are needed and are currently being investigated for other possible phenomena over large deformations such as phase changes and microstructural phenomena related to new metal alloys and nanostructured materials.

4 CONCLUSIONS

The development and application of mathematical models to predict the microstructure evolution during metal forming is of great importance in order to obtain a reliable process control. Coupling these models to finite element method can be a powerful tool for processes involving large plastic strains, allowing a better understanding and control of process parameters that influence dynamic and static phenomena, allowing optimizing the whole processes getting a higher quality final product, avoiding long “tryout” stages.

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